The global demand for LNG in 2016 was ca. 260 MTPA. This is projected to double to over 500 MTPA by 2030. As the market grows, the composition and characteristics of demand are changing, providing greater opportunity for small to mid-scale LNG developments. Costs for conventional onshore, base loads plants declined in the 1990’s as larger capacity trains were introduced, but this trend reversed in recent years, particularly in Australia where baseload LNG project costs have approached $4000/TPA due to high labor costs and “stick” construction in remote locations.

Floating LNG offers the potential to unwind the cost spiral by moving the construction work to shipyards and fabrication yards, while eliminating the cost for long pipelines to shore and extensive civil works and large scale construction housing on site.

By the end of 2016, four FLNG projects had been sanctioned, showing that FLNG is generally accepted in the industry as feasible. The focus is now on technology selection, liquefaction & storage capacity, and safe operational considerations, particularly with regard to LNG offloading.

Concerns typically raised with proposed FLNG concepts include:

1. Size, weight and complexity of topsides
2. Topsides hydrocarbon inventory and impact on safety design
3. LNG offloading method and sea-state limitations
4. Overall project cost, schedule and uncertainty
5. Design for generic application/residual value

Additional general considerations, not unique to FLNG, include:

1. Method and cost for well drilling, completion, workover
2. Subsea architecture
3. Exposure to cyclonic storms or other extreme metocean conditions
SIMPLIFYING FLOATING LNG

FLNG System Configuration – Integrated Arrangement

Most FLNG concepts on the market utilize an integrated FLNG vessel that incorporates all functions into a single vessel including:

- primary processing
- gas treatment
- NGL fractionation
- Liquefaction
- storage of condensate/NGL/LNG
- offloading of each product from storage

This approach leads to very large and complex purpose built vessels.

Other cost and design factors in FLNG include the use of proprietary liquefaction technology (licensing fees), topsides weight, layout congestion & safety hazards due to hydrocarbon inventory/explosive overpressure, and limitations on LNG offloading operations except for the most benign metocean conditions.

Processing requirements for treating wellhead gas to LNG inlet quality vary considerably from field to field depending on

- condensate/gas ratio
- acid gas and nitrogen levels
- ethane, propane and butane content & LPG marketing
• method for hydrocarbon dewpointing

It is not practical to design a single generic topsides process scheme to deal with the wide range of conditions that may be encountered if the FLNG vessels has to produce two, three or more fields over its useful life. However, once the gas has been treated and is rendered suitable for liquefaction, the design requirements for liquefaction, storage and offloading of the LNG are the same from one field to another, varying only according to capacity.

**FLNG System Configuration – Split Arrangement**

The LoneStar FLNG concept was designed to circumvent many of the cost and design concerns of the conventional, “integrated”, FLNG concepts. The concept is based on de-integrating or splitting the system between:

1) a field specific upstream facility for primary processing, and gas treatment and
2) a generic LNG liquefaction/storage/offloading vessel

Splitting the overall FLNG arrangement between a conventional upstream host facility and a generic, standardized liquefaction vessel results in:

- an overall reduction in complexity and cost
- an increase in design flexibility and residual value for re-deployment.

Design features of the split system include:

1. Conventional, proven, “off-the-shelf” designs for both upstream host facility
2. Standardized, generic design for liquefaction vessel based on converted Moss LNG ship
3. Segregation of functions between processing/gas treating & liquefaction
4. Pre-cooled, Dual N2 expander liquefaction for compactness, safety and simplicity
5. DFDE prime movers on liquefaction vessel for improved efficiency
6. Multiple parallel construction paths, modularized and repetitive design/build

Segregating the FLNG functions between different facilities provides several benefits for cost, safety, project schedule and operations.
Separating the FLNG functions between different facilities provides several benefits for cost, safety, project schedule and operations.

- Site specific development considerations are addressed in upstream host facility
- Standardized, generic liquefaction vessel for redeployment and residual value
- Improved project execution through use of conventional designs and parallel construction
- Offloading via DP shuttle tanker for reliable operations in open water
- Mobile liquefaction vessel can avoid severe weather or dry dock for repairs.
- Dual N2 expansion liquefaction provides compactness and light weight, safety benefits & ease of refrigerant makeup with N2, easier operability, and proven track record on LNG ships of similar systems.

The combined impact of the Split Process concept not only reduces the capital cost of the FLNG system, but also expands the envelope of application for FLNG to fields in metocean environments that are currently beyond FLNG development consideration.
LIQUEFACTION VESSEL CONVERSION

The liquefaction vessel is based on a standard Moss type LNG carrier of 155 – 170,000 m³ capacity and equipped with Dual Fuel Diesel Electric (DFDE) propulsion. The Moss containment system eliminates risk of damage from sloshing in slack tanks during filling. There is no documented evidence of sloshing damage to the tanks in a Moss type LNG containment system although some early designs required reinforcement of the pump tower foundations.

A standard LNG carrier with DFDE power plant will have 30 – 40 MW of installed power. This is increased by 72 MW of installed power by adding 4 x 18 MW MAN V18 DF 51/60 engines in a new mid-ship section engine room. The power required to drive a 2 MTPA liquefaction plant is approximately 70 MW, depending on gas composition and cooling water temperature. The four mid-ship engines provide primary liquefaction power while the existing ships power plant is electrically interconnected to provide sparing and redundancy.

The 30 m long mid-ship “sandwich” section is spliced in between the Nos. 2 and 3 cargo tanks and houses:

- 4 x 18 MW DFDE engine gensets
- disconnectable turret, turret trunk & auxiliaries
- switchgear including transformers, variable frequency drives & magnetic bearing controls
- seawater/freshwater heat exchangers & cooling water pumps

By inserting the sandwich piece at mid-ship, any increased hull stresses resulting from increasing the waterline length are primarily in the new section and can be accommodated in the design. The turret contains a single 10 in. NB, ANSI 900 gas swivel to deliver pre-cooled gas to the liquefaction vessel from the host platform. The turret contains an additional swivel for a deep seawater intake hose to provide cold seawater for process cooling. At a depth of 1500 ft., typical seawater temperatures will be 48 – 50 F.
The turret is designed for quick connect/disconnect (< 4 hours). Maximum seastate for turret connection is $H_s \leq 4$ m and for disconnect $H_s \leq 5.5$ m. Once the turret is connected, the liquefaction vessel can remain on station in any weather condition subject to design of the buoy mooring system, although it would not be planned to remain on station for extreme weather such as tropical cyclonic storms or severe winter storms at high latitudes.

The sandwich piece provides a footprint for the liquefaction module. The liquefaction module contains 2 x 1 MTPA liquefaction trains arranged port and starboard. Each train consists of:

- 1 x Cold Box containing 5 x Braised Aluminum Heat Exchanger (BAHE) cores
- 1 x “Warm Loop” and 1 x “Cold Loop” Turbo Expander/Compressors
- 3 x Integral Sealed N2 compressors (ISC)
- Printed Circuit Heat Exchanger (PCHE) inter-stage coolers
- 3 x Labyrinth seal Boil-off Gas (BOG) compressors (shared between 2 trains)
- 1 x Liquid Expander

ISC compressors are directly driven by a high speed electric motor which is housed within the compressor body. The motor and impellers are installed on a common shaft supported on magnetic bearings and is cooled by a slipstream of the gas being compressed. The entire assembly is hermetically sealed within the compressor body with no external shaft seals.
Benefits of the ISC include:

- extremely compact footprint
- no shaft seals or seal gas system
- no lube oil system
- no gearbox
- high reliability with minimal planned maintenance

ISC’s were originally developed for remote, unmanned pipeline booster stations. In recent years, they have been selected for seabed compression. The use of ISC’s and the elimination of nearly all hydrocarbon inventory in the liquefaction system enables the liquefaction module to be extremely compact and lightweight. Overall dimensions of a 2 MTPA liquefaction module are approximately 16 m long x 17 m high x 45 m wide.

In contrast to most FLNG vessels, because the liquefaction vessel described here is simply a modified ship, it can remain classed, flagged and crewed as a ship and periodically dry dock for emergency repair and maintenance. This operating philosophy is expected to significantly reduce capex and opex compared to a liquefaction vessel which must be designed to remain on station indefinitely and which much be crewed as a production unit.

For liquefaction capacities up to 1.5 MTPA, the liquefaction vessel can be based on conversion of an existing 138,000 m3 Moss steamship.
LNG OFFLOADING

The ability to reliably transfer LNG from the liquefaction vessel to an LNG tanker is crucial to the successful operation of any offshore FLNG installation. Most FLNG concepts have been constrained to utilize some form of “Side-by-Side” offloading where a standard LNG ship is maneuvered into position with tugs and berthed alongside the FLNG vessel, typically against Yokohama fenders.

Side by Side loading entails several operational limitations and risks including:

- Seastate limitations < 2m Hs
- Limits on tug effectiveness with increasing Hs
- Relative motions between vessels
- Risk of collision when berthing/un-berthing
- Exceeding safe tensions in mooring lines & appurtenances

To avoid risk of collision, common practice in deepwater offshore upstream operations is to avoid having vessels approach within the 500 m exclusion zone of a production facility unless the vessel is dynamically positioned and rated to DP2 capability. Standard LNG ships do not have DP2 capability.

60 T ASD tug effectiveness in waves - Tp=10s
Some form of “Tandem Offloading” is usually proposed to overcome the limitations of “Side by Side” loading. Tandem Offloading requires use of a DP shuttle tanker or tug assist and the increased distance between vessels can result in higher rates of Boil Off Gas (BOG) compared to Side by Side loading.

In the LoneStar FLNG concept, a special form of tandem loading offloading is utilized incorporating the following features:

- DP2 LNG Shuttle Tanker
- Floating Cryogenic Hoses
- “Bow to Bow” offloading orientation in close proximinty

The liquefaction vessel weathervanes around the midship turret using thruster assist – similar to turret moored drill ships from the 1970’s and 80’s. It is normally oriented stern into the wind. This keeps the living quarters upwind of the liquefaction plant and offloading operation.

The DP2 shuttle tanker is equipped with a DFDE propulsion system. Three retractable azimuthing thrusters are added, two at the stern and one at the bow, along with an upgraded bow tunnel thruster. This provides a DP envelope capable of over 40 kts wind longitudinally or 20 kts on the beam, more than adequate for offloading in moderate metocean conditions.
Time domain simulations of the DP system in a metocean environment of 20 kts wind and 2.4 m Hs show that it is capable of holding the bow of the ship within a watch circle of approximately 5 m diameter.

During offloading the two vessels are oriented bow to bow, with a separation distance of about 50 m, approximately equal to the ships beam. The relatively small overlap between the two bows along the longitudinal axis reduces the risk of collision in spite of the small separation between vessels. If the shuttle tanker loses station keeping, it will drift aft, away from the liquefaction vessel.

The liquefaction vessel is equipped with reels for 3 x 16 in floating cryogenic hoses and the DP shuttle is equipped with a retractable bow loading manifold. Two hoses are for liquid transfer and one for vapor return.

![Graph showing LNG Ship Bow Motion Wind on Bow](image)

Longer hose lengths require higher pumping power which imparts heat energy into the LNG stream. The relatively short hose length in the bow to bow configuration reduces pump power during offloading, reducing boil off gas rates. If all three hoses were used for liquid transfer, at
6500 m³/hr total transfer rate the BOG rate is 6 tonnes/hr, which could be handled by a re-liquefaction system on the shuttle tanker rather than using a vapor return line.

UPSTREAM FACILITY CONSIDERATIONS

The Split FLNG concept can be adapted to a wide range of applications by selecting a host facility suitable for the site specific gas composition, water depth, metocean conditions, well drilling and intervention method, condensate storage & handling, etc. Host facilities that have been considered for various cases including:

- FPSO – circular, spread moored
- FPSO – ship shape, turret moored
- Fixed Platform – conventional or self-installing
- Concrete Gravity Base Platform (GBS)
- Tension Leg Platform
- Production Semi-submersible

Case studies using three different upstream host facilities are discussed further.
LIQUEFACTION TECHNOLOGY

Dual N2 Expansion liquefaction (DNX) was selected for liquefaction because of the following advantages:

- compact/lightweight
- intrinsically safe
- convenient refrigerant makeup
- simple operability/restart/maintenance
- proven track record on LNG carriers

The primary concerns or drawbacks typically cited against DNX are:

- process efficiency/fuel consumption
- lack of large scale plants

Liquefaction Process Optimization

Through a series of process improvements, it was found that unit power for N2 expansion could be reduced about 6% to 425 KW-hr/Tonne LNG by increasing feed gas pressure and N2 discharge pressure from ca. 900 psi to 1300 psi.

Unit power is reduced by 20% from the Base Case by further lowering the interstage cooling temperature on the N2 compressors from 100 F to 60 F. In practice, this would be achieved by a deep seawater intake hose – seawater at 1500 ft. depth is 47 – 50 F, with little sensitivity to surface temperature.

A further reduction of overall unit power to 325 KW-hr/Tonne LNG, (28% less than the Base Case) is achieved by pre-cooling the feed gas from 80 F to -20 F. The pre-cooling is achieved by heat integration with the hydrocarbon dew pointing system/export booster compression on the host facility and/or use of a CO2 refrigeration system. The power requirement for pre-cooling is included in the total liquefaction power.
DNX Optimization: Total Unit Power (KW-hr/Tonne)

The unit power cited above includes the power on the host facility for both feed gas booster compression and pre-cooling on the host plus the liquefaction power on ship. Focusing on the latter, the power required to drive the liquefaction plant on board the ship is reduced by 34% compared to the Base Case, from 64,500 HP to 42,500 HP for each 1 MTPA train.

The ship power is mainly for N2 compression, but also includes BOG compression and a power “credit” from the liquid expander.

Unit power in the Optimized Case for DNX is still higher than typical values for Single Mixed Refrigerant or Dual Mixed Refrigerant processes. However, the higher thermal efficiency of the DFDE power plant, 44% net of switch gear losses vs. 38% for an aero-derivative gas turbine, compensates this difference in unit power. Total fuel consumption (host facility + ship) for liquefaction power is reduced from 7% of feed gas in the Base Case to 5.2% in the Optimized Case.
Thus, the Optimized DNX liquefaction process with DFDE power achieves near parity in fuel efficiency compared to mixed refrigerant processes, but retains the benefits of safety, compactness, lightweight and operational flexibility which are intrinsic to N2 liquefaction processes.

**Background and Experience with N2 Expansion Liquefaction**

N2 expansion liquefaction has been used in dozens of LNG peakshaver plants. However, the refrigeration duty is significantly less than that required for a baseload LNG facility. There are over 50 LNG vapor re-liquefaction plants in service on board LNG carriers based on N2 liquefaction, but these are typically small scale, single expander processes with much higher unit power than DNX systems.

Dual N2 expansion is the standard process used in the air separation industry to fractionate liquid oxygen (LOX) from the atmosphere with scores of air separation plants using this process all around the world for decades; a large percentage of these plants have LOX capacity of 1 MTPA equivalent or greater.

Large scale N2 cycle cooling for LNG was successfully accomplished for the first time on the AP-X® LNG Process trains in Qatar, for which the subcooling refrigeration loop utilizes a N2 process that has equivalent refrigeration duty to liquefy 1 to 2 MTPA of natural gas if it were a stand-alone liquefier.

The two FLNG vessels built for Petronas will produce 1.2 MTPA and 1.5 MTPA respectively utilizing a triple N2 expansion process provided by Air Products AP-NTM, finally confirming full acceptance of N2 expansion liquefaction processes for application on offshore FLNG vessels.
DEVELOPMENT CASE STUDIES

Timor Sea – Australia

The Timor Sea lies between northern Australia and New Guinea and contains several discovered, but undeveloped gas fields in WD ranging from 300 – 500 ft. The metocean conditions are moderate, punctuated with seasonal tropical cyclones. Gas compositions are typically lean with low condensate yields, but with high CO2 content, typically > 12 mole percent.

A conventional fixed steel jacket was selected for the host facility to provide a cyclone resistant, stable wellhead platform for drilling and production with a separate, larger fixed platform for gas processing. The wellhead platform handles basic separation and depletion compression. A 2-level integrated gas treatment platform provides the following gas processing functions for 300 MMSCFPD:

- Primary & Secondary Membranes for bulk CO2 removal to < 3%
- Amine Unit for final acid gas removal
- Mole Sieve dehydration
- Mercury Absorption Beds
- Turbo-expander for hydrocarbon dewpointing
- Fractionation Tower for separation of residue gas from CO2 after Secondary Membrane

The 1.5 MTPA liquefaction vessel is designed as described previously, except that a used 138,000 m3 Moss carrier is converted. The liquefaction vessel would disconnect from the turret and evacuate the field in advance of an approaching cyclone. A semi-submersible provides both accommodation and tender support for platform drilling operations.
A concept was investigated for dry gas fields in 2500 – 4000 ft. WD offshore W Australia. The metocean conditions are moderate to severe with 100 year cyclone winds = 105 knots (1 hr.) and Hs = 55 ft. Gas compositions are typically lean with low condensate yields, but with high CO2 content, typically > 12 mole percent.

A TLP was selected for the host facility to provide cyclone resistant, stable platform for gas processing and well completion/workovers. Gulf of Mexico experience shows that TLP’s are proven for withstanding tropical storms in these water depths. The TLP hull has 4 x 62 ft. OD columns on 203 ft. spacing with 100 ft. draft. These dimensions are similar to deepwater Gulf of Mexico TLP’s.

The TLP hull and topsides would be mated at the fabrication yard and dry towed to a nearby port. The 2-level integrated topsides provides the following gas processing functions, arranged in 1 train x 300 MMSCFDPD, sufficient for 2 MTPA.

- Primary & Secondary Membranes for bulk CO2 removal to < 3%
- Amine Unit for final acid gas removal
- Mole Sieve dehydration
- Mercury Absorption Beds
- Turbo-expander for hydrocarbon dewpointing
- Fractionation Tower for separation of residue gas from CO2 after Secondary Membrane
- Amine unit for acid gas removal

TLP hull sizing is sensitive to topsides weight, so wells would either be pre-drilled using a MODU or drilled from the TLP using Tender Assist Drilling. The 2 MTPA liquefaction vessel is designed as described previously based on a new build 155K m3 DFDE ship. The liquefaction vessel would disconnect from the turret and evacuate the field in advance of an approaching cyclone. A semi-submersible provides both accommodation and tender support for platform drilling operations.